Vol. XXI.—No. 116] [March, 1927.

THE MINERALOGICAL MAGAZINE

AND

Journal of The Mineralogical Society

(*INSTITUTED FEBRUARY 8, 1876.*)

WITH A SEPARATELY-PAGED APPENDIX OF

MINERALOGICAL ABSTRACTS

EDITED BY L. J. SPENCER, F.R.S.

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LONDON:
HUMPHREY MILFORD, OXFORD UNIVERSITY PRESS,
AMEN HOUSE, WARWICK SQUARE, E.C. 4.

1927.

Price 6s. net.
Annual Subscription for four numbers, Post free 20s.

MINERALOGICAL SOCIETY

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PROCEEDINGS

OF THE

MINERALOGICAL SOCIETY

EXCERPT MINUTES OF COUNCIL MEETING.

Held in the Apartments of the Geological Society, Burlington House, London, W., January 19, 1926, *at* 4 *p.m.*

Prof. W. W. Watts, F.R.S., President, in the Chair.

The deaths of Mr. R. H. Solly and Mr. J. P. Wintringham were announced.

Mr. George MacDonald Davies and Mr. Hugh Alexander Ford were provisionally elected Ordinary Members of the Society.

The audited accounts and balance-sheet for the year ending December 31, 1925, submitted by the Treasurer, were approved.

In accordance with bye-law 7 it was decided to remove from the list of members the names of three members who had been reported to the Council at the January meeting last year.

A letter from Messrs. Simpkin, Marshall, Hamilton, Kent & Co. was read, in which they announced their decision to discontinue the periodical branch of their business and that in consequence they could no longer act as publishers to the Society. The Editor was directed to write accepting their resignation and thanking them for their past services to the Society. It was decided to accept the terms offered by Mr. Humphrey Milford, Oxford University Press, for publishing the Journal.

The Committee appointed to consider the celebration of the Jubilee of the Society submitted a provisional programme. This was approved, and it was decided further that there should be an informal dinner on February 2, at which members would have the opportunity of discussing the arrangements for the formal celebration in September. Messrs. A. Brammall and A. Russell were appointed as additional members on the Jubilee Committee. The Secretary was instructed to send, on February 3, letters of congratulation to Messrs. B. Kitto, A. Liversidge, and J. L. Wills, who had been members of the Society since 1876.

GENERAL MEETING.

Held in the Apartments of the Geological Society, Burlington House, London, W., January 19, 1926, *at* 5.30 *p.m.*

Prof. W. W. Watts, F.R.S., President, in the Chair.

Twenty-three Members and five Visitors were present.

The elections of Messrs. G. M. Davies and H. A. Ford were confirmed.

The President announced the provisional programme which had been approved for the celebration of the Jubilee of the Society.

The following papers were then read:—

1. Some mineralogical transformations in crystalline schists: by Dr. C. E. Tilley (p. 34).

2. Gold and silver in the Dartmoor granite: by Dr. A. Brammall (p. 14).

3. On the chemical classification of the mica group. II. The basic micas: by Mr. A. F. Hallimond (p. 25).

4. The construction and use of an X-ray goniometer: by Mr. G. Greenwood (p. 1).

EXCERPT MINUTES OF COUNCIL MEETING.

Held in the Apartments of the Geological Society, Burlington House, London, W., March 16, 1926, *at* 4 *p.m.*

Prof. W. W. Watts, F.R.S., President, in the Chair.

The death of Dr. F. Krantz, a former member of the Society, was announced.

Prof. William George Fearnsides and Mr. Thomas Crawford Phemister were provisionally elected Ordinary Members of the Society.

Arrangements made for the Jubilee Celebration in September were reported.

GENERAL MEETING.

Held in the Apartments of the Geological Society, Burlington House, London, W., March 16, 1926, *at* 5.30 *p.m.*

Prof. W. W. Watts, F.R.S., President, in the Chair.

Fifteen Members were present.

The elections of Prof. W. G. Fearnsides and Mr. T. C. Phemister were confirmed.

The following papers were read:—

1. Molecular volume relations in the mica group: by Mr. A. F. Hallimond (p. 195).

2. Smithsonite from the Rhodesia Broken Hill mines: by Mr. E. D. Mountain (p. 51).

3. The identity of the Cobija and Lampa meteoric stones: by Mr. E. D. Mountain (p. 87).

4. On garnet in pelitic contact-zones: by Dr. C. E. Tilley (p. 47).

Mr. Mountain exhibited a specimen and microscope slides in illustration of his paper on meteorites.

EXCERPT MINUTES OF COUNCIL MEETING.

Held in the Apartments of the Geological Society, Burlington House, London, W., June 15, 1926, *at* 4 *p.m.*

Sir Thomas Holland, F.R.S., Vice-President, in the Chair.

The deaths of Prof. W. J. Lewis, Past-President and for many years Librarian of the Society, Mr. W. B. Giles, Mr. H. B. Guppy (a former member), and Mrs. F. Henson (a former member) were announced.

Mr. Gerald Andrew, Mr. Alan Stuart, and Mr. Frank Coles Phillips were provisionally elected Ordinary Members of the Society.

The Treasurer reported that he had represented the Society at the meeting convened by the British Association and the Society of Antiquaries on the question of the exemption of Scientific Societies from the payment of Income Tax.

A new scheme and scale of charges for sets of the Journal, vols. I–X and XI–XX, proposed by the Treasurer, were approved. It was also decided that copies of numbers of which the stock was reduced to 30 or less be reserved for sets and that individual copies of such numbers should not be sold except by special permission of the Council.

The following changes in the list of Officers and Council were approved for recommendation to the Members of the Society: Ordinary Members of Council—Prof. H. L. Bowman, Prof. W. T. Gordon, Dr. H. F. Harwood, and Dr. G. F. Herbert Smith, in place of the four retiring Members of Council, Sir William Bragg, Mr. Barker, Mr. Russell, and Mr. H. G. Smith.

It was decided to hold four meetings next year on the following dates: Tuesdays, January 18, March 15, June 14, and November 1, 1927.

The Editor reported that a prospectus of the 'Mineralogical Magazine' had been prepared and issued by the new Publisher.

It was agreed that the General Index to vols. XI–XX should be issued as a special part without number.

It was decided that 'Tschermaks Mineralogische und Petrographische Mitteilungen' be replaced on the list of exchanges of publications; and that the sale price of the two parts of the 'Proceedings of the Crystallological Society' should be 4*s.* each.

A letter was read from Sir John Flett, who had represented the Society at the International Geological Congress at Madrid, stating that in future the Congress would devote a special section to Mineralogy and Petrology.

GENERAL MEETING.

Held in the Apartments of the Geological Society, Burlington House, London, W., June 15, 1926, *at* 5.30 *p.m.*

Prof. HAROLD HILTON, Vice-President, in the Chair.

Thirteen Members and one Visitor were present.

The elections of Messrs. G. Andrew, A. Stuart, and F. C. Phillips as Ordinary Members of the Society were confirmed.

The following papers were read :—

1. On the nature of berthierite: by Dr. F. L. Stillwell (p. 83).

2. On some chloritic minerals associated with the basaltic Carboniferous rocks of Derbyshire: by Mr. S. I. Tomkeieff (p. 73).

3. The anomalous optical properties of some new series of isomorphous double tartrates: by Mr. H. E. Buckley (p. 55).

4. Sperrylite crystals from the Transvaal: by Dr. L. J. Spencer (p. 94).

5. Three South African meteorites: Vaalbult, Witklip, and Queens Mercy: by Dr. G. T. Prior (p. 188).

EXCERPT MINUTES OF COUNCIL MEETING.

Held in the Apartments of the Geological Society, Burlington House, London, W., November 2, 1926, *at* 4 *p.m.*

Prof. W. W. WATTS, F.R.S., President, in the Chair.

The deaths of two Honorary Members, Prof. H. Baumhauer and Prof. C. M. Viola, were announced.

Dr. Conrad Robert Burri, Dr. Harry von Eckermann, Prof. Stefan Kreutz, Dr. Maharajapuram Sitaram Krishnan, and Prof. Charles Palache were provisionally elected Ordinary Members of the Society.

A letter from the Royal Society was read announcing the grant of £100 from the Government Publication Fund in aid of the publication of 'Mineralogical Abstracts'.

The accounts of the Jubilee Entertainment Fund were presented by the Treasurer, and on the motion of Prof. Hutchinson it was decided that the final balance should be applied to printing the account of the Jubilee Celebrations in the Magazine.

A motion by Dr. Prior that the names of certain of the foreign delegates and guests present at the Jubilee Celebrations be brought before the General Meeting for election as Honorary Members was carried.

Mr. A. F. Hallimond and Dr. W. F. P. McLintock were appointed auditors of the accounts for the year ending December 31, 1926.

The draft Annual Report of Council submitted by the Secretary was read and approved.

The Librarian presented a detailed report on the recent overhauling of the Library of the Society.

It was decided that the Royal Society of New South Wales be replaced on the list of exchanges of publications.

GENERAL (ANNIVERSARY) MEETING.

Held in the Apartments of the Geological Society, Burlington House, London, W., November 2, 1926, *at* 5.30 *p.m.*

Prof. W. W. Watts, F.R.S., President, in the Chair.

Twenty-one Members and four Visitors were present.

The President nominated Messrs. F. H. Butler and E. D. Mountain to act as scrutineers of the voting-papers for the election of Officers and Council. The scrutineers reported that thirty-two voting-papers had been returned to the Secretary, and that the list as nominated by the Council was approved, namely :—

President. Prof. W. W. Watts, Sc.D., LL.D., F.R.S.

Vice-Presidents. Prof. Harold Hilton, M.A., D.Sc.
Sir Thomas H. Holland, K.C.S.I., K.C.I.E., D.Sc., F.R.S.

Treasurer. F. N. Ashcroft, M.A., F.G.S., F.C.S.

General Secretary. G. T. Prior, M.A., D.Sc., F.R.S.
Foreign Secretary. J. W. Evans, C.B.E., D.Sc., LL.B., F.R.S.
Editor of the Journal. L. J. Spencer, M.A., Sc.D., F.R.S.

Ordinary Members of Council.

A. F. Hallimond, M.A., F.G.S.
J. A. Howe, O.B.E., B.Sc., F.G.S.
W. Campbell Smith, M.C., M.A., F.G.S.
C. E. Tilley, Ph.D., B.Sc., F.G.S.
Prof. P. G. H. Boswell, O.B.E., D.Sc., F.G.S.
T. Crook, A.R.C.Sc.I., F.G.S.
L. Hawkes, D.Sc., F.G.S.
H. H. Thomas, M.A., Sc.D., F.G.S.
Prof. H. L. Bowman, M.A., D.Sc., F.G.S.
Prof. W. T. Gordon, M.A., D.Sc., F.R.S.E.
H. F. Harwood, M.Sc., Ph.D., A.I.C.
G. F. Herbert Smith, M.A., D.Sc., F.G.S.

The elections of Dr. C. R. Burri, Dr. Harry von Eckermann, Prof. Stefan Kreutz, Dr. M. S. Krishnan, and Prof. Charles Palache as Ordinary Members of the Society were confirmed.

Prof. Reinhard Brauns, Prof. Louis Duparc, and Prof. Friedrich Rinne were, by ballot, elected Honorary Members of the Society.

A vote of thanks to the Geological Society for the use of their rooms, proposed by Mr. Mountain and seconded by Colonel Belaiew, was carried.

The General Secretary then read the following Annual Report of Council:—

During the Session 1925–6 four ordinary meetings have been held (by kind permission) in the apartments of the Geological Society, Burlington House, London, W., at which sixteen papers were read.

Four numbers of the Journal (nos. 111–114), containing thirteen papers and 427 abstracts, have been issued quarterly. No. 111 contains no papers but is made up of indexes to vol. 20 of the Magazine and vol. 2 of the Abstracts, together with a topographical index. The Society is greatly indebted to the Editor for the preparation of these indexes, for which as many as 15,000 slips were required. In no. 112, commencing vol. 21, are included, for the first time in the Magazine, a few advertisements. During the Session, Messrs. Simpkin, Marshall, Hamilton, Kent & Co. having expressed their wish to discontinue the publication of the Magazine, Mr. Humphrey Milford of the Oxford University Press was appointed as the new publisher.

The balance-sheet for the year ending December 31, 1925, showed that the financial position of the Society was sound. The assets (exclusive of the Library and stock of the publications) amounted to £1,541 19*s.* 8*d.*, with no liabilities. The value of the stock invested in the names of the Trustees of the Society was on that date £1,162 11*s.* 3*d.*, corresponding to £24 10*s.* 8½*d.* for each Life-Member. A sum of £100 was granted by the Royal Society from the Government Publication Fund in aid of the publication of 'Mineralogical Abstracts'.

During the Session the Society has lost by removal for non-payment of subscriptions four Ordinary Members; and by death two Honorary Members, namely Prof. H. Baumhauer and Prof. C. M. Viola, and four Ordinary Members, namely Prof. W. J. Lewis, one of the members of the Crystallological Society and a Past-President and Librarian, Mr. R. H. Solly, also one of the members of the Crystallological Society, Mr. J. P. Wintringham, and Mr. W. B. Giles. Twelve Ordinary Members have been elected. The total number of members on November 1, 1926, was 190, of whom ten are Honorary Members. Of the Ordinary Members 47 are Life-Members.

The outstanding event of the Session has been the Celebration of the Jubilee of the Society, a full account of which will appear in the December number of the Magazine. The Celebration, which was attended by ten Delegates appointed by various Mineralogical and Geological Societies and by seven invited foreign guests, was generally agreed to have been an unqualified success. For this success the thanks of the Society are due to all those who contributed so generously to the entertainment fund, and more particularly to Mr. Ashcroft, who undertook the arrangements for the official dinner and the accommodation of the guests; to Mr. Campbell Smith, to whom was entrusted the organization of the conversazione; and to the directors of the two excursions, Prof. Hutchinson and Mr. Arthur Russell.

The Council has to congratulate the Society on its continued scientific activity and prosperity.

On the motion of Dr. Herbert Smith, seconded by Dr. Harwood, the Report was adopted.

The following papers were then read:—

1. Schultenite, a new mineral, from South-West Africa: by Dr. L. J. Spencer, with a chemical analysis by Mr. E. D. Mountain (p. 149).

2. Aramayoite, a new mineral, from Bolivia: by Dr. L. J. Spencer, with a chemical analysis by Mr. E. D. Mountain (p. 156).

3. X-ray examination of aramayoite: by Miss Kathleen Yardley (p. 163).

4. The structure of baddeleyite and of prepared zirconia: by Miss Kathleen Yardley (p. 169).

5. The crystalline structure of zircon: by Mr. W. Binks (p. 176).

Specimens and models were exhibited by the authors of the papers, and corroded crystals of quartz from Switzerland by Mr. F. N. Ashcroft.

MINERALOGICAL

ABSTRACT OF RECEIPTS AND PAYMENTS

GENERAL PUR-

Receipts.	£	s.	d.	£	s.	d.
By Balance brought forward from 1925—						
1. At Bankers :						
(*a*) Current Account	42	7	4			
(*b*) Deposit Account	115	0	0			
2. In Office	1	1	4			
				158	8	8
Annual Subscriptions—						
1. Current year	118	13	0			
2. Arrears	6	6	0			
3. Advance	9	9	0			
				134	8	0
Entrance Fees				13	13	0
Composition Fees				31	10	0
Sale of Publications—						
1. During 1925 :						
By Publishers (£218 9*s.* 0*d.*, less trade discount £36 8*s.* 2*d.*, commission £22 15*s.* 1*d.*, and postage £0 0*s.* 6*d.*)	159	5	3			
2. During 1926 :						
(*a*) By Publishers (part year) (£10 15*s.* 6*d.*, less trade discount £1 15*s.* 11*d.*, commission £1 15*s.* 11*d.*, and postage £0 0*s.* 6*d.*)	7	3	2			
(*b*) By Custodian of Stock (£60 18*s.* 0*d.* less trade discount £0 6*s.* 5*d.*, and distribution charges £4 19*s.* 8*d.*[1])	55	11	11			
				222	0	4
Interest on Investments—						
1. £1,150 5% War Loan Inscribed Stock[2]	52	17	6			
2. £50 5% National War Bonds 1927 Registered	2	10	0			
3. £50 4% Funding Loan Inscribed Stock	2	0	0			
				57	7	6
Deposit Interest				10	19	7
Government Grant from Publication Fund administered by the Royal Society				100	0	0
Transferred from Jubilee Entertainment Fund Account—						
1. For cheques used	0	3	4			
2. Contribution toward cost of publication of the account of the Jubilee Celebrations	25	15	0			
				25	18	4
				£754	5	5

[1] Includes refund of carriage on set sold in 1925, authorized Nov. 1, 1926.
[2] Includes investments made during the year.

SOCIETY.

FOR THE YEAR ENDING DECEMBER 31, 1926.

POSES ACCOUNT.

Payments.	£ s. d.	£ s. d.
To Printing and distributing the Mineralogical Magazine Nos. 112–115 inclusive and the General Index to Vols. XI–XX (Oxford University Press)—		
1. Printing	394 10 3	
2. Illustrations	27 14 9	
3. Authors' Copies	22 13 0	
4. Jubilee Celebration, Reprints	4 14 6	
5. Printed postal wrappers (renewal of stock)	1 9 0	
6. Distribution Charges	15 14 6	
		466 16 0
Miscellaneous Printing (not annual)—		
1. Bye-Laws and List of Members (extra copies)	3 2 6	
2. Notice *re* change of Publishers	9 6	
3. Notice *re* General Index to Vols. XI–XX	13 6	
4. Treasurer's Notices (renewal of stock)	18 6	
		5 4 0
Printing and distributing notices of Meetings and other annual miscellaneous printing		14 1 9
Expenses at Meetings, 1926—		
1. Operator of lantern	1 1 0	
2. Porter	1 0 0	
		2 1 0
Care of Stock of Publications, 1926 (J. Mugford)		1 1 0
Editor's Honorarium, 1926	25 0 0	
Do., Special for Index to Vols. XI–XX	25 0 0	
		50 0 0
Postage—		
1. Hon. Secretary	17 9	
2. Editor	2 5 6	
3. Hon. Treasurer (not charged)		
		3 3 3
Bank charges, cheque book, and other small items		10 8
Investments (including composition fees received during the year), purchase of £100 5% War Loan Inscribed Stock, commission and stamps		101 6 9
Balance, December 31, 1926—		
1. At Bankers :		
(*a*) Current account	9 13 3	
(*b*) Deposit account	100 0 0	
2. In Office	7 9	
		110 1 0
		£754 5 5

Examined and compared with vouchers and found correct.

W. F. P. McLINTOCK } Auditors.
A. F. HALLIMOND }

January 17, 1927.

F. N. ASHCROFT, Hon. Treasurer.

LIBRARY FUND

Receipts.	£ s. d.	£ s. d.
By Balance brought forward from 1925—		
At Bankers :		
1. Current Account	3 6 6	
2. Deposit Account	50 0 0	
		53 6 6
Deposit Interest		18 3
		£54 4 9

BALANCE

Liabilities.	December £ s. d.
Excess of assets over liabilities	1574 18 9
	£1574 18 9

ACCOUNT.

PAYMENTS.

	£	s.	d.
To Binding of Periodicals	40	15	9
Balance, December 31, 1926—			
At Bankers	13	9	0
	£54	4	9

Examined and compared with vouchers and found correct.

W. F. P. McLINTOCK, A. F. HALLIMOND } Auditors.

January 17, 1927. F. N. ASHCROFT, Hon. Treasurer.

SHEET.

31, 1926.

ASSETS.	£	s.	d.	£	s.	d.
Balances—						
I. General Purposes Account:						
1. At Bankers:						
(*a*) Current Account	9	13	3			
(*b*) Deposit Account	100	0	0			
2. In Office		7	9			
				110	1	0
II. Library Fund Account:						
At Bankers				13	9	0
Sale of Publications—						
1. By Publishers, April 1 to Dec. 31, 1926 (estimate)	190	0	0			
2. By Custodian		5	0			
				190	5	0
Investments at Broker's Valuation—						
1. £1,150 5% War Loan Inscribed Stock at 100⅞	1160	1	3			
2. £50 5% National War Bonds 1927 Registered at 106¾	53	7	6			
3. £50 4% Funding Loan Inscribed Stock at 85½	42	15	0			
				1256	3	9
Arrears of Annual Subscriptions, valued at				5	0	0
				£1574	18	9

The Stock of Publications and the value of the Library are not included in the above assets.

January 17, 1927. F. N. ASHCROFT, Hon. Treasurer.

ABSTRACT STATEMENT OF ACCOUNTS OF THE JUBILEE ENTERTAINMENT (VOLUNTARY) FUND, 1926.

Receipts.	£	s.	d.	Expenditure.	£	s.	d.
Voluntary contributions	149	17	6	Expenditure to Dec. 31, 1926	149	16	11
Sale of Dinner tickets .	40	10	0				
Deposit Interest . .		12	6	Transferred to the General Purposes Account towards cost of publication of the account of the Jubilee Celebrations .	25	15	0
				Balance	15	8	1
	£191	0	0		£191	0	0

W. F. P. McLINTOCK, A. F. HALLIMOND } Auditors.
F. N. ASHCROFT, Hon. Treasurer.

January 17, 1927.

Note.—A detailed statement will be issued to the subscribers to the fund when the account is closed. The balance available, after settlement of an estimated liability of £3 and such further expenditure as may properly be charged to the fund, will be transferred to the General Purposes Account as a further contribution towards the cost (about £45) of printing the account of the Jubilee Celebrations.

THE MINERALOGICAL MAGAZINE

AND

JOURNAL OF

THE MINERALOGICAL SOCIETY.

No. 116. March, 1927. Vol. XXI.

On the chemical classification of the mica group. III. The molecular volumes.

By A. F. Hallimond, M.A., F.G.S.

Assistant Curator, Museum of Practical Geology, London.[1]

[Read March 16, 1926.]

IT is unfortunate that so many published analyses of mica are not accompanied by the physical data for the material used. Nevertheless, enough information is available to permit a general comparison of the density relations for the group. This is most conveniently made in terms of the specific volume, for, in most isomorphous series, the volume is an additive property even when the molecular volumes of the end-minerals differ appreciably. Such a relationship will be shown to hold good approximately for the micas; the volume can be calculated from constants assigned to the constituent oxides, the difference from the observed value being rarely more than 2 per cent. This result does not, of course, imply the adoption of any particular chemical theory; but it is convenient to work in terms of molecular volumes, and for that purpose

[1] Communicated by permission of the Director.

the theory outlined in the earlier parts of the present paper[1] has been adopted. The micas are regarded as salts of an acid with a constant number (6) of silicon atoms; and the volume associated with $6SiO_2$ is accordingly taken as the 'molecular volume' (mean); for formulae based on $3SiO_2$ the volumes would, of course, be one-half the values given. The group has already been divided into sections of differing chemical composition, and the several divisions are reflected in the scheme of molecular volumes now obtained (fig. 6). This, however, is simply the consequence of the fact that the volume is an additive property, and is true whatever formulae are adopted; but the present formulae are to a certain extent supported by the fact that the molecular volumes derived from them are such as would be expected in an isomorphous group; they are all of the same order of size, but differ sufficiently to agree with the view, already advanced on grounds of chemical composition, that the various sections have limited miscibility.

The fact that the volume is an additive property will be used in discussing the state of combination of titanium. In the micas that element (as TiO_2) is assumed to replace silica, and the amount present is frequently high enough for the volume data to afford good evidence in favour of this view. But several authors have considered the possibility that titanium is present as Ti_2O_3 or in some other form, and in one outstanding case it will be shown that the volume data can best be explained by the presence of titanium in a form not isomorphous with silica; for chemical reasons it would seem to be present as TiO_2 rather than as Ti_2O_3.

Calculation of the molecular volumes.—If, as in the present theory, the mica molecule contains the same number (n) of silicon atoms in all members of the group, it becomes possible to calculate the 'molecular volume' (V), i.e. the volume occupied by the matter associated with $nSiO_2$, directly from the silica percentage (a) and the density (ρ), by means of the following formula

$$V(\text{obs.}) = \frac{n \times 60 \times 100}{a \times \rho}.$$

The result is independent of all theory as to the nature of the substituent groups (provided they do not contain silica), and includes matter present in solid solution. It can, indeed, be applied in any mineral group for the purpose of investigating whether, for a proposed set of formulae, the scheme of molecular volumes is consistent with the

[1] Min. Mag., 1925, vol. 20, pp. 305–318, and 1926, vol. 21, pp. 25–33. Figures 1–5 and Tables I–IV were given in those parts.

isomorphous relationship known to exist between the members of the group.

All the volumes for the micas to be given below are referred to $6SiO_2$. For trisilicic molecules the values would of course be halved. If titanium

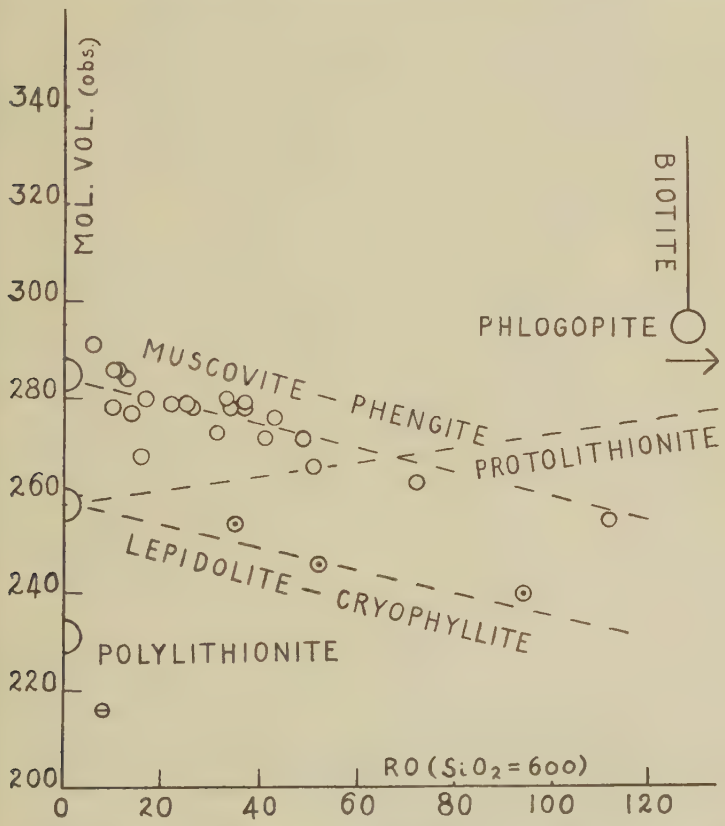

Fig. 6. Molecular volumes for the mica group. The points shown represent observed values, the large circles being the values calculated for the pure compounds. Biotite and phlogopite if plotted against their RO-content would lie far to the right of the diagram ; their range of volume has been indicated for comparison with that of the acid micas.

is present as TiO_2 replacing silica it is necessary to correct the silica percentage by adding $\frac{3}{4}$ of the TiO_2 percentage, while the total material is reduced from 100 to $(100 - \frac{1}{4}TiO_2)$. In some analyses the silica

percentage is given for material dried at 105°C., while the density refers to air-dried material; for mica, however, this source of error is not serious and has been ignored. The 'observed' molecular volumes in the following pages are those obtained by the above formula. The 'calculated' values are derived from the molecular proportions of RO, R_2O_3, and Li_2O by means of constants according to the following equation (see p. 200):

$$V\text{ (calc.)} = 165 + 0{\cdot}40\ (R_2O_3) + 0{\cdot}15\ (RO) + 0{\cdot}13\ (Li_2O),$$

(R_2O_3), &c., being the equivalent numbers for the respective oxides when $SiO_2 = 600$, as given in the present tables. Observed and calculated values show close agreement throughout the whole group, as will be seen from the data for the various sections below.

(*a*) *Muscovite–phengite.*—

Analysis.[1]	RO.	*V* (obs.).	*V* (calc.).	Analysis.	RO.	*V* (obs.).	*V* (calc.).
Dana, 3 ...	6	291	288	Kunitz, 11 ...	33	280	285
Kunitz, 1 ...	10	286	290	,, 6 ...	34	278	280
,, 4 ...	10	278	282	,, 7 ...	37	278	278
Dana, 4 ...	11	286	289	,, 5 ...	37	279	278
Kunitz, 2 ...	13	284	286	,, 9 ...	41	272	279
Boeke, 38 ...	14	277	279	Dana,			
Dana, 8 ...	16	268	279	'biotite' 6 ...	43	276	288
Kunitz, 3 ...	17	280	283	,, 15 ...	49	272	279
Dana, 1 ...	22	279	286	,, 10 ...	51	266	278
Kunitz, 8 ...	25	279	279	,, 17 ...	72	263	262
Dana, 2 ...	26	278	284	,, 18 ...	112	255	262
Kunitz, 10 ...	31	273	276				

These values indicate a progressive contraction as the proportion of phengite increases, a result that might be anticipated for the replacement of Al_2O_3 by the small group RO. The decrease in volume is about 25 units for the introduction of 100RO; this is the value used to ascertain the constant for Al_2O_3 (p. 200). The volume of pure muscovite is taken to be 285.

(*b*) *Lepidolite.*—The older analyses yield the following values:

Analysis.	*V* (obs.).	*V* (calc.).	Analysis.	*V* (obs.).	*V* (calc.).
Dana, 1	250	260	Dana, 4	259	258
,, 2	249	262	Kunitz, 3	244	246

The rather high difference in Dana (2) corresponds with a deficiency in $(K,Na)_2O$.

[1] See Part I of this paper, p. 317.

Additional lepidolites (not given in Part I).—

	R_2O_3.	RO.	R_2O_3+RO.	Li_2O.	$(K,Na)_2O$.	H_2O.	F_2.	H_2O+F_2.	V (obs.).	V (calc.).
Genth[1] ...	131	27	158	103	95	24	138	162	234	235
Hall[2] ...	158	5	163	114	97	—	—	—	240	243
Simpson[3] ...	159	19	178	135	95	17	150	167	245	249
Gibson[4] ...	167	12	179	141	106	7	145	152	257	253

The first two analyses from Dana are incomplete; unfortunately there seems to be no record of the density of a normal lepidolite, though the formula is supported by a series of good analyses. In the analyses last quoted the alkalis agree well with the ratio $K_2O : 6SiO_2$, but in all cases except one the amount of lithia exceeds the simple value 100, so that these minerals are presumably mixed with polylithionite; while the analyses of Genth and Hall show a deficiency of bases and can be represented as belonging to the series lepidolite–irvingite. Thus in all these cases the volumes will be somewhat below that for the simple formula. The volume 13 has been assigned to Li_2O since this yields satisfactory calculated values for all the lithia micas, including those given above; the calculated volume of true lepidolite is then 258.

(*c*) *Lepidolite–cryophyllite* (Part I, p. 317).—

Analysis.	RO.	V (obs.).	V (calc.).	Analysis.	RO.	V (obs.).	V (calc.).
Lepidolite (theory) ...	0	—	258	Kunitz, 5 ...	52	246	249
Kunitz, 4 ...	35	254	257	Dana, 3 ...	94	240	240

The replacement of R_2O_3 by RO is marked by a contraction analogous with that in the muscovite–phengite series. (See fig. 6.)

(*d*) *Polylithionite* (Part I, p. 318).—The only density available yields the volume 216. Potash has largely been replaced by soda (p. 201), so that this value will no doubt be lower than that of the potash compound, which has the calculated volume 231; allowing for this, it is clear that the further substitution of lithia for the alumina in lepidolite has again diminished the volume by about 27 units for the introduction of $100Li_2O$.

[1] F. A. Genth, Amer. Journ. Sci., 1892, ser. 3, vol. 44, p. 388; Japan.

[2] A. G. Hall, Victoria Mines Report for 1908, 1909, p. 66; Coolgardie.

[3] E. S. Simpson in A. N. Winchell, Amer. Journ. Sci., 1925, ser. 5, vol. 9, p. 424; Coolgardie.

[4] C. G. Gibson in A. N. Winchell, ibid., Coolgardie, Western Australia.

(*e*) *Lepidolite-protolithionite* (Part I, p. 318). The analyses discussed in Part I indicate that this series is derived from lepidolite by addition of RO; at the basic end of the series Li_2O is replaced by RO.

Analysis.	V (obs.).	V (calc.).	Analysis.	V (obs.).	V (calc.).
Kunitz, 8	264	266	Stelzner	306	305
,, 9	266	268	Kunitz, 10 ...	286	279
Dana, 8	328	305	,, 11 ...	296	290

In obtaining the 'calculated' volumes allowance is not made for the high alkali-content which has no doubt raised the observed values for Dana (8) and Kunitz (10).

(*f*) *Irvingite* (Part I, p. 318).—Unfortunately the density is not recorded, but two analyses already given under lepidolite suggest the existence of a continuous series of mixtures between the two minerals. The calculated volume is 206 (11 units being deducted since only $1H_2O$ is present).

(*g*) *Phlogopite.*—The observed volumes are:—Dana ('System', p. 633) (1) 289, (2) 293, (8) 288, (11) 297, (12) 293. These indicate for pure phlogopite the value $V = 295$. Phlogopite is derived from muscovite by the substitution of 2RO for $2Al_2O_3$, coupled with the addition of 4RO. The molecular volume of muscovite is 285. If we assume that the replacement of Al_2O_3 here produces the same volume-change (25 units) as in the muscovite-phengite series, the molecular volume V of the 'additional' RO can be calculated as follows:

$$295 = 285 - 25 \times 2 + V \times 4.$$

The volume of 'additional' RO is therefore 15. This is really the value for MgO, but it will be shown that in the biotites the substitution of FeO for MgO does not produce any marked disturbance in the volumes.

If the volume of substituent RO is also 15, and $V(Al_2O_3 - RO) = 25$, the molecular volume 40 must be assigned to Al_2O_3. The volume of the common mica-nucleus $K_2O \cdot 6SiO_2 \cdot 2H_2O$ (i.e. muscovite $- 3Al_2O_3$) is therefore $285 - 3 \times 40 = 165$, and the volume of any given mica is to be calculated by adding to this nucleus the volumes due to R_2O_3, RO, and Li_2O according to the following equation

$$V(\text{mica}) = 165 + 0{\cdot}40(R_2O_3) + 0{\cdot}15(RO) + 0{\cdot}13(Li_2O),$$

(R_2O_3), &c., being the equivalent numbers for the respective oxides when $SiO_2 = 600$, as given in the tables appended to Parts I and II of this paper. The values so obtained are the 'calculated' values given in the present note. Throughout the whole group the difference between

observed and calculated values rarely exceeds 2 per cent., and nearly every instance of greater deviation is at once seen to be related to the presence of an abnormal amount of alkali or of water.

(*h*) *Other basic micas.*—Observed and calculated volumes for the new analyses have already been given in Table III (Part II, p. 31). The agreement is very satisfactory, the only serious differences (except no. 44) being explained by the presence of additional water (1), excess or deficiency of potash (17, 19, 20, 22, 43), and the replacement of potash by soda (24). In the same way the following results from older data show good agreement.

Analysis.	V (obs.).	V (calc.).	Diff.	Analysis.	V (obs.).	V (calc.)	Diff.
Dana, 1 ...	314	317	−3	Boeke, 76 ...	336	332	4
,, 2 ...	310	307	3	,, 99 ...	326	325	1
,, 5 ...	326	321	5	,, 133 ...	311	307	4
,, 7 ...	309	312	−3	,, 134 ...	293	295	−2
,, 11 ...	312	317	−4	,, 135 ...	282	290	−8
,, 22 ...	314	306	8	,, 136 ...	312	305	7
,, 29 ...	330	326	4	,, 137 ...	300	302	−2
,, 31 ...	317	313	4	,, 190 ...	307	303	4

It is clear from the close agreement throughout the group that the substitutions of Fe_2O_3 for Al_2O_3, and of FeO for MgO, cause no great disturbance in the molecular volume. This accords with the close isomorphous relations between those oxides.

Substitution of sodium for potassium.—The 'calculated' volumes given are based on the assumption that all the alkali is present as potash. Calculated values for the soda micas will therefore differ from the observed values by an amount equal to $V(K_2O) - V(Na_2O)$. Thus:

Paragonite (Part I, p. 317).—

Analysis.	V (obs.).	V (calc.).	Diff.
Dana, 2	279	295	16
,, 4	259	280	21
,, 6	267	288	21

Allowing for the low water content in Dana (4), $V(K_2O) - V(Na_2O)$ is approximately 15. This agrees with the data for polylithionite, where the replacement of two-thirds of the potash by soda together with the loss of $1H_2O$ corresponds with a deficiency of 15 units in the observed volume.

Volumes of H_2O and F_2.—Considerable variation in the amount of these constituents has but little effect on the molecular volume, so that their volume cannot be large. Consideration of a number of extreme

cases, like biotite (new) no. 1, points to a value between 10 and 15 for H_2O, while it is clear from the phlogopites (p. 200) that replacement of $(OH)_2$ by F_2 causes but little alteration.

Valency of titanium.—In calculating the molecular ratios for the present tables it has been assumed that titanium is present as the dioxide, isomorphous with SiO_2. This is the view taken by Kunitz, and the older analyses in general yield simpler values for the ratio $K_2O : SiO_2$ if titanium is included with the silica. Here the molecular volumes afford a more sensitive indication than do the molecular ratios, as will be seen from the analyses of titaniferous micas tabulated in full below (Table V). For each analysis the upper line (*a*) shows the result of including titania with silica in the usual way, while the second line (*b*) gives the values when titania is taken along with the group R_2O_3. The first four micas, which are representative of those tabulated earlier in this paper, give quite normal values by the first method (top lines), and the observed and calculated values agree ; but the volumes obtained by the second method (lower lines) show throughout a larger difference from the calculated values, and in two cases lie outside the usual limits for biotite. The agreement between observed and calculated volumes for the titaniferous micas in the tables already given would thus seem to imply that the titanium has been correctly assigned to TiO_2 replacing silica. The last analysis in this group of Table V appears, however, to indicate a transition to those of the second group.

The analyses in the second group of Table V were not included in the general tables. They show an unusually high content of titanium, and normal values are found in the *second* lines. If the titanium is included with SiO_2 (top lines) the volumes are well outside the usual limits for biotite, there is a marked difference between the observed and calculated values, and the other data are less consistent with the values for ordinary biotites. It would seem, therefore, that the titanium cannot be regarded as replacing silica, but must be placed either in the group R_2O_3 or as an independent constituent. There are serious chemical difficulties in admitting the presence of Ti_2O_3 in a mineral containing ferric iron, but the case may be comparable with the admixture of $(Mg,Fe)O.TiO_2$ in haematite.

Further light on the behaviour of titanium is afforded by the data for the mineral astrophyllite given in the third section of Table V. In this mineral, which is evidently closely allied to the micas, the content of alumina is small ; but the total value for R_2O_3 (including the titanium) is still about 100, as in phlogopite, and the other data resemble those for

Table V. Biotite: molecular ratios and volumes when (*a*) (Si,Ti O_2 = 600 *and* (*b*) SiO_2 = 600.

	TiO_2 %.		R_2O_3.	RO.	$(K,Na)_2O$.	H_2O.	F_2.	$H_2O + F_2$.	*V* (obs.).	*V* (calc.)	Diff.
1. Typical biotites with TiO_2 replacing SiO_2.—											
Kunitz, 11 ...	3·06	(*a*)	199	464	99	217	—	—	315	314	1
		(*b*)	243	505	108	236	—	—	345	338	7
Kunitz, 12 ...	2·56	(*a*)	180	489	101	239	—	—	314	310	4
		(*b*)	216	525	108	257	—	—	339	330	9
Boeke, 190 ...	3·16	(*a*)	164	482	97	191	5	196	307	303	4
		(*b*)	193	513	104	203	5	208	330	319	11
Dana, 22 ...	4·73	(*a*)	179	459	104	119	—	—	314	306	8
		(*b*)	230	508	115	129	—	—	351	333	18
Boeke, 135 ...	7.68	(*a*)	164	395	107	50	—	—	282	290	−8
		(*b*)	238	457	124	58	—	—	333	329	4
2. Abnormal biotites from the shonkinite of Katzenbuckel, Baden; TiO_2 replacing R_2O_3.—											
Doelter, 101...	10·86	(*a*)	104	418	82	76	—	—	248	270	−22
		(*b*)	193	509	103	96	—	—	310	318	−8
Doelter, 102...	12·02	(*a*)	121	388	89	48	—	—	251	271	−20
		(*b*)	224	487	111	60	—	—	324	328	−4
Rosenbusch[1] .	12·56	(*a*)	84	370	84	32	14	46	—	—	—
		(*b*)	177	459	104	39	18	57	—	—	—
3. Astrophyllite; titanium replacing R_2O_3.—											
Dana,[2] 1 ...	7·09	(*b*)	108	502	104	104	—	—	296	284	—
„ 5 ...	11·11	(*b*)	98	559	110	200	26	226	—	—	—
„ 6 ...	13·58	(*b*)	134	421	95	198	—	—	295	282	—
„ 7 ...	11·4	(*b*)	95	485	117	233	—	—	—	—	—

Small amounts of zirconium (up to 5 per cent.) have been included with SiO_2 and the volumes are calculated accordingly.

the micas. When plotted on the diagram given in figure 5, the four points lie along the lower boundary of the biotite area. The volumes agree fairly well, but the unusual composition prevents a close comparison, since the volumes of zirconium and titanium are not accurately known. Physically, though closely resembling a biotite, the mineral is brittle with a pseudo-tetragonal percussion figure, and has distinctive optical characters. It constitutes, therefore, an independent species, but is

[1] H. Rosenbusch (A. Osann), 'Gesteinslehre', 5th edit., 1923–24, p. 224. 'Wodanite.' The other two analyses are given in the 3rd edition, 1910, p. 201. [Min. Abstr., vol. 2, p. 11.] It will be noted that these micas have an abnormally low content of water.

[2] Dana's 'System', 1892, p. 719. Small amounts of CaO, &c., are omitted.

apparently related to the biotites in somewhat the same way as the biaxial mineral bassetite is related to the uniaxial torbernite. Structural modifications of this kind are often accompanied by little or no change in the molecular volume. The Katzenbuckel mica, on the other hand, would seem to be a true biotite in physical properties as well as in general composition.

True molecular volumes.

The values given represent the volume in cubic centimetres occupied by the molecular weight in grams. Since an atom of hydrogen is known to weigh $1{\cdot}66 \times 10^{-24}$ grams, the real volumes occupied by the respective atoms or groups can at once be ascertained. These volumes include the interspaces, and the partition of a crystal into separate domains for the constituent oxides appears at first sight purely arbitrary. But the volumes given are based, not upon any arbitrary form of cell, but upon the expansion effect due to the introduction of a known amount of the oxide into a space-lattice common to the mica group. The lattice behaves within certain limits like a liquid or an extensible network, and the volume-constant for an oxide in mica can be as precisely defined, though it is not so accurately known, as that for a salt dissolved in a liquid. The following table summarizes the data here ascertained for the micas:

Oxide.	Molecular volume V.	True molecular volume = $V \times 1{\cdot}66 \times 10^{-24}$
R_2O_3	40	$66{\cdot}4 \times 10^{-24}$
RO	15	24·9 ,,
Li_2O	13	21·6 ,,
$K_2O.6SiO_2.2H_2O$ ...	165	274 ,,
Also (less accurately known):		
K_2O	41	68 ,,
Na_2O	26	43 ,,
SiO_2	17	28 ,,
H_2O	11	18 ,,

The temperature-range of formation for tourmaline, rutile, brookite, and anatase in the Dartmoor granite.

(With Plates IV and V.)

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[Read January 18, 1927.]

THE range of temperature within which tourmaline can arise in nature has not hitherto been determined. No synthesis of this mineral is on record, and experimental data are therefore lacking. On the other hand, rutile, brookite, and anatase have all been prepared synthetically, and the experimental data suggest that rutile is formed at the highest temperatures, brookite at temperatures considerably lower, and anatase at a point still lower on the scale. It is generally conceded that for rutile a pyrogenic origin is possible, and that brookite and anatase appear only as secondary minerals. The status of tourmaline as a possible pyrogenic mineral is regarded as doubtful by Clarke,[1] who states that 'in igneous rocks tourmaline seems to have been produced by fumarole action, and not as a direct separation from the magma'.

Within the Dartmoor area tourmaline is so widespread, and its modes of occurrence are so varied, that it invites an attempt to date its birth relative to that of associated minerals, and thus to determine its status as a possible pyrogenic mineral.

For such investigations Wright and Larsen[2] indicate the utility of quartz as a 'geological thermometer', and they established some important generalizations to which appeal may be made in determining the

[1] F. W. Clarke, 'The data of geochemistry', 1924, p. 417.

[2] F. E. Wright and E. S. Larsen, 'Quartz as a geologic thermometer'. Amer. Journ. Sci., 1909, ser. 4, vol. 27, pp. 421–447.

stability-ranges of associated minerals—in the present case tourmaline, rutile, brookite, and anatase. For the purposes of this discussion the range of the 'thermometer' will be extended to include temperatures fixed for tridymite and cristobalite. Each of these three crystalline forms of silica exists in two modifications (α and β), but for present purposes discrimination is necessary between the α and β forms of quartz only. The thermometric scale shown diagrammatically in fig. 1 is based mainly on results recorded by Quensel,[1] Day and Shepherd,[2] Wright and Larsen (loc. cit.), Rinne and Kolb,[3] Koenigsberger,[4] and White.[5]

The Modifications of Quartz: Generalizations established by Wright and Larsen.

At ordinary temperatures all quartz is α-quartz, which at 575° C. undergoes enantiotropic inversion to β-quartz, the inversion being heralded through an interval of about 400° by continuously increasing rates of expansion and by changes in optical properties. On both rising and falling temperature the inversion is sharp and prompt.

Idiomorphic crystals of α-quartz tend to be prismatic in habit, to display unequal development of the terminal planes, and to develop trigonal trapezohedra. The symmetry class is trapezohedral-tetartohedral (trigonal holoaxial). Right- and left-handed forms are more frequent and are more readily compounded as twins in the α-phase than in the β-phase, α-quartz being merely a distortion of the β-structure.[6] Vein-quartzes, geode-quartzes, and the quartz of certain pegmatites originated as the α-phase, or low-temperature form.

Idiomorphic crystals of β-quartz tend to be bipyramidal in habit, and to display equal development of the terminal planes, trigonal trapezohedra being absent. The symmetry class is trapezohedral-hemihedral (hexagonal holoaxial).[7] The quartz of granite-pegmatites, graphic peg-

[1] P. Quensel, Centralblatt Min., 1906, p. 728.

[2] A. L. Day and E. S. Shepherd, Amer. Journ. Sci., 1906, ser. 4, vol. 22, p. 276.

[3] F. Rinne and R. Kolb, Neues Jahrb. Min., 1910, vol. ii, p. 138.

[4] J. Koenigsberger and W. J. Müller, Centralblatt Min., 1906, p. 371.

[5] W. P. White, Amer. Journ. Sci., 1919, ser. 4, vol. 47, p. 1.

[6] R. E. Gibbs, 'The polymorphism of silicon dioxide and the structure of tridymite'. Proc. Roy. Soc. London, Ser. A, 1926, vol. 113, pp. 351–368.

[7] R. W. G. Wyckoff, 'The crystal structure of the high temperature (β-) modification of quartz'. Amer. Journ. Sci., 1926, ser. 5, vol. 11, pp. 101–112. [Min. Abstr., vol. 3, p. 183.]

matites, granites, and porphyries originated as the β-phase, or high-temperature form.

On the passage of either phase through the inversion-point, the original external form tends to persist, but internal molecular rearrangement occurs. The consequences entailed by the crystallographic rela-

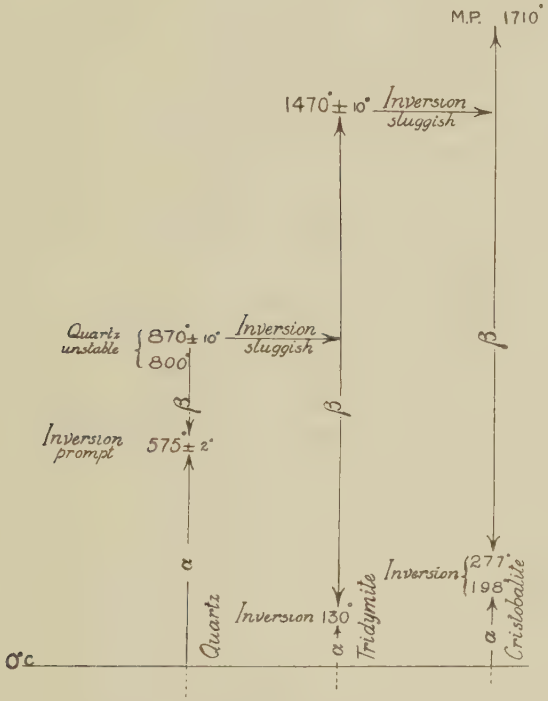


Fig. 1. Geological thermometer.

(See foot-note 3, p. 218)

tions between the two phases include internal effects which serve to indicate whether quartz has ever passed through the inversion-point. These effects are (1) intricate actual or potential fracturing, brought to light by etching a basal plate with cold hydrofluoric acid for $1\frac{1}{4}$ hours, and (2) intricate and irregular twinning. Basal plates of quartz are of rare occurrence in granite sections. The etch-test applied by us to several of the granular aggregates to be described has yielded only indecisive results.

Syntheses of crystalline silica and titanic oxides: their significance.

Methods of synthesizing the various forms of silica fall into three main groups involving respectively (1) simple ignition or dry fusion, (2) the use of dry fluxes, and (3) the use of aqueous fluxes under pressure.[1]

Syntheses effected by the simple ignition of silica glass, quartz crystals, quartz sand, or the simple dry fusion of quartzose rock resulted in the production of tridymite or cristobalite at temperatures which are in general agreement with the stability-range indicated by the scale. So also are the products of processes involving the use of 'dry' fluxes.

On the other hand, K. Chrustschoff's experiments[2] showed that by the use of aqueous fluxes the high-temperature forms cristobalite and tridymite can be produced at temperatures well within the stability-range of the low-temperature form α-quartz: cristobalite at 180°–228°, quartz at 240°–300°, tridymite at 310°–360°, tridymite and quartz together at 300°–520° (approx.).

Thus though quartz has been produced artificially only at temperatures below 800°, tridymite and cristobalite, which in dry melts would not ordinarily form below 800°, have been produced artificially in aqueous fluxes at much lower temperatures. Similarly, the crystallization of felspars from aqueous melts is known to be possible at temperatures considerably lower than those at which they would ordinarily crystallize out from relatively 'dry' melts.

This effect of aqueous-flux conditions is also suggested by the known temperature relations between rutile, brookite, and anatase. Experimental data[3] suggest for these three species a 'high', 'low', and 'lower' temperature-range of formation respectively, but the three arise together in some of the reddened and tourmalinized varieties of the Dartmoor granite. In artificial syntheses[4] rutile has been produced either by ignition at high temperatures or by the use of anhydrous fluxes engaging neither fluorides nor chlorides; whereas in every case (with one possible exception[5]) in which either brookite or anatase was identified among

[1] Cited by F. W. Clarke, loc. cit., pp. 361–366.

[2] K. Chrustschoff, Amer. Chemist, 1873, vol. 3, p. 281; Compt. Rend. Acad. Sci. Paris, 1887, vol. 104, p. 602; Neues Jahrb. Min., 1897, vol. i, p. 240.

[3] Summarized by F. W. Clarke, loc. cit., p. 355.

[4] Described and discussed by F. W. Clarke, loc. cit., pp. 354–356.

[5] B. Doss (Neues Jahrb. Min., 1894, vol. ii, p. 147) fused titanic oxide in beads of either microcosmic salt or borax in a loop of platinum wire. Anatase was produced only in the beads of microcosmic salt; borax beads yielded only rutile. The crystals of anatase were too minute (0·1 mm.) for accurate gonio-

the products, synthesis engaged water or compounds of fluorine or chlorine. It is a significant fact that a typical environment in which brookite and anatase may originate together is that produced by pneumatolysis accompanied by the production of tourmaline and quartz with or without gilbertite, fluorite, topaz, and chalcedony.

The foregoing data will now be co-ordinated and applied.

Tourmaline : the range of its crystallization-temperature.

A convenient starting-point is afforded by the somewhat rare geodes occurring in the normal granite, e. g. that quarried at Merrivale. The structure of the Merrivale geodes comprises something more than the mere crystal-infilling of an irregular cavity.[1] The cavity wall is only the inner surface of a distinct wall-zone in which the geode crystals may be more or less deeply rooted. The geode structure as a whole may be regarded as beginning at the outer surface of the wall-zone in contact with the normal biotitic granite. The crystals infilling the cavity comprise :

(*a*) Euhedrons of orthoclase, the faces of which are often encrusted with minute flakes and rosette-clusters of gilbertite inshot with slender needles of tourmaline—often very pale in colour (blue, lilac, brown, greenish-brown), sometimes almost colourless.

(*b*) Large crystals of clear quartz occasionally showing the characteristic development of the α-phase. These quartz crystals commonly enclose numerous needles and prisms of tourmaline orientated indiscriminately and often projecting beyond the limits of the quartz crystals.

(*c*) Gilbertite as irregular masses, or rosette-clusters up to one inch in diameter. These clusters are sessile on quartz, felspar, and tourmaline indifferently. The gilbertite (K_2O 10·35, Na_2O 1·26, H_2O 4·34 %) is in obvious reaction relation [2] to the perthitic orthoclase.

(*d*) Deep purple fluorite, as irregular masses, often intimately intergrown with gilbertite, felspar, quartz, and tourmaline.

(*e*) Long stout prisms of dark-coloured tourmaline. The voids between large crystals of quartz, felspar, gilbertite, &c., are often bridged by these tourmaline prisms, the ends of which are embedded in the crystals flanking the voids.

metric measurement, and were identified on the evidence of chemical tests and of angles measured by means of the microscope.

[1] When a liquid (e. g. water, critical temperature 374°) containing a dissolved salt is heated above its critical temperature the salt is also volatilized. (J. H. L. Vogt, Econ. Geol., 1926, vol. 21, p. 218.)

[2] N. L. Bowen, 'The reaction relation in petrogenesis'. Journ. Geol., 1922, vol. 30, pp. 177–198.

(*f*) Thin square micaceous tablets of emerald-green torbernite, lying on the felspar or on the aggregates of gilbertite. These were apparently the last crystals to form.

(*g*) Very rare and minute flakes of gold.

From the fact that quartz crystals which project into the cavity occasionally display the characteristic features of the α-phase, it may be inferred that the quartz, and therefore also its inclusions of tourmaline, crystallized at a temperature below 575°.

The wall-zone is essentially free from biotite. Texturally, it may be pegmatite, graphic granite, granite, or even microgranite. Its constituent minerals are those found in the cavity itself: felspar, quartz, tourmaline, fluorite, and gilbertite. Long euhedral prisms of tourmaline showing the characteristic cross-sections are common. Flakes of torbernite have been detected in minute drusy cavities.

The outer part of this wall-zone merges into the biotitic groundmass of the granite, the quartz of which, according to Wright and Larsen, originated as the β-phase, and therefore at a temperature above 575°. Hence this wall-zone connotes the temperature-interval $575° \pm x°$, with 575° as a mean.

Tourmaline occurs in the Merrivale granite itself, in the closely allied Foggintor and Sweltor types, and in the Dartmoor granite generally. Thin sections of the granite often show anhedral tourmaline in such textural relationship to quartz, felspar, and mica as to indicate for it a genesis approximately contemporaneous with that of one or other of these major constituents. The selected cases described below will serve to illustrate this fact.

Plate IV, fig. 1, shows greenish-brown tourmaline in a granite composed of albite, perthitic orthoclase, perthitic microcline, pinitized cordierite, and a little biotite. A few irregular masses of tourmaline are partly or wholly surrounded by felspar, but in the main the tourmaline is interstitial to quartz, and the two minerals appear to be almost contemporaneous products of a highly siliceous residual flux. The textural role of quartz thus associated with tourmaline does not differ appreciably from that of the quartz in the tourmaline-free portions of the rock-slice figured, and if for the quartz a pyrogenic origin is conceded, the tourmaline with which it is associated has a claim to the same status. According to Wright and Larsen, quartz in granites crystallized at some temperature above 575° and below 800°, and hence for the tourmaline in this particular case a temperature of formation $575° + x°$ is implied.

Plate IV, fig. 2, shows similar tourmaline in quasi-eutectic intergrowth

with quartz in a thin layer of pegmatite lying parallel to a pseudo-bedding-plane in the granite at the Merrivale quarry. Attempts to determine, by Wright and Larsen's etch-test, whether the quartz originated in the α- or the β-phase resulted in wholly indecisive results, but the genesis of the tourmaline was certainly contemporaneous with that of the quartz.

Plate IV, fig. 3, shows a similar quasi-eutectic of quartz and tourmaline around a porphyritic felspar in a garnetiferous graphic granite. Blebs of 'graphic' quartz are enclosed in the felspars shown and some of these blebs contain tourmaline. According to Wright and Larsen, the quartz in graphic granites originated as the β-phase or high-temperature form, and hence the tourmaline (in part at least) originated at the temperature $575° + x°$. The figure illustrates the penetrative power of a residual and highly siliceous borosilicate flux which retained some of the constituents of tourmaline until a comparatively late stage in the process of crystallization.

The penetrative power and the reactivity of such a residual flux is clearly revealed also in figs. 4 and 5 (Plate IV), showing garnetiferous cordierite-biotite-granite in which both biotite[1] and felspar have undergone tourmalinization around relatively large 'pools' of clear quartz. Texturally these quartz 'pools', within and around which tourmalinization has occurred, are in marked contrast to the normal groundmass quartz, and their origin is referred by the authors to a late stage in the process of crystallization, a step which is warranted by two significant facts:

(1) Steel-blue anatase of tabular habit has replaced certain inclusions (probably apatite) in the original biotite. Two such replacements occur in the tourmaline shown in the centre of each of figs. 4 and 5 (Plate IV). The larger of the two in fig. 5 is shown in detail in fig. 6.

(2) Secondary tourmaline showing finger-like outgrowths penetrating adjacent felspars is not uncommon. A similar habit is displayed even more emphatically by occurrences of muscovite in granite from the Haytor quarry and elsewhere. In some cases this habit in muscovite is closely imitated by quartz, the locus of the two minerals being intimately related to quartz 'pools'. The mica has the aspect and general properties of true muscovite, as distinct from the yellowish gilbertite occurring in the Merrivale geode-structures. The 'reaction relation' between muscovite and orthoclase has its analogue in the described relation of tourmaline to felspar and biotite together: both the muscovite and the

[1] Dartmoor biotite contains up to 1·9 % of titanic oxide.

tourmaline originated from reaction of residual flux with previously crystallized minerals. If for the muscovite a pyrogenic status is claimed the same status may be accorded to the tourmaline, and therefore also in this particular case to the by-product of tourmalinization, namely, the anatase replacing apatite. The necessity for distinguishing between 'pyrogenic primary' and 'pyrogenic secondary' minerals is evident.

In the more heavily biotitic granites the biotite often presents to adjacent quartz an irregular margin fringed with minute finger-like projections (Plate IV, fig. 7 *a*) the tips of which are sometimes converted to tourmaline. Such occurrences of tourmaline imply that constituents of tourmaline such as boric acid were retained in a residual flux until quartz had almost completed its crystallization, when their concentration attained the degree necessary for reaction with biotite to form secondary tourmaline. Figs. 7 *b* and 7 *c* show tourmaline developed in quartz 'pools' between biotite crystals. In fig. 7 *b* the growth of the irregular masses of tourmaline probably began before that of the biotite finished. In fig. 7 *c* the minute euhedral hemimorph of tourmaline completely enclosed in biotite suggests that the tourmaline was actually in existence before biotite completed its growth. The same fact is indicated by the relationship of tourmaline to ilmenite and biotite in fig. 7 *d*: here ilmenite occurs as a marginal precipitation in biotite; but the tourmaline figured was actually in place before biotite-growth ceased, for at least two of the ilmenite grains are moulded on the tourmaline.

The evidence so far adduced shows that the genesis of tourmaline may occur within the temperature-range $575° \pm x°$, the lower limit of this range being the temperature at which the Merrivale geodes were infilled, the upper limit that at which biotite was completing its growth.

On the further evidence described below this range may be extended upwards. The minute tourmaline euhedron occurring as an inclusion in biotite (Plate IV, fig. 7 *c*) is not unique: similar euhedrons have been noted among the minute zircons in the insoluble residue after the baueritization[1] of biotite in bulk. Similar euhedrons occasionally occur as inclusions in porphyritic felspar, which may also completely enclose nests of tourmaline prisms. Moreover, tourmaline has been observed in sector-twinned cordierite which, though originating usually as a groundmass constituent, may itself be porphyritic and has often been noted among the inclusions in porphyritic felspar.

The temperature-range of formation for tourmaline may thus be

[1] A. Brammall and H. F. Harwood, 'The occurrence of rutile, brookite, and anatase on Dartmoor'. Min. Mag., 1923, vol. 20, p. 22, foot-note references.

extended to cover the range for biotite-growth and to overlap that of porphyritic constituents. A similar inference may be drawn from a study of the peripheral features of certain types of quartz-tourmaline nodes; these have already been described in some detail.[1] The upper limit of the range thus extended is uncertain; but as quartz often occurs as an inclusion in porphyritic felspar a temperature higher than 800° cannot be assumed: $575° + x°$ is probably below 800°.

Reference may here be made to the abundance of tourmaline in many granitic veins and sheet-intercalates which the authors class broadly as 'elvans'. Occasionally aplitic in facies, they are essentially granites, but of relatively fine grain. As Wright and Larsen established the fact that the quartz in porphyries originated as the β-phase or high-temperature form, it is probable that the quartz in these elvan-types originated in the same phase. The genesis of tourmaline in these types presents no special features not covered by the cases already described.

Reference has also been made to the reaction effects produced by residual aqueous and borosilicate fluxes at a late stage in the crystallization processes. Confinement of these residuals under pressure inhibited the escape of their more volatile constituents, and reaction between them and solid mineral-phases in their environment proceeded to completion where the residuals accumulated.

The release and escape of these volatile constituents from fluid granitic material injected along fissures is well illustrated by an occurrence on the south side of Mel Tor. Near the base of the tor a nearly vertical vein of microgranite containing a little tourmaline is traceable upwards for several yards until its outcrop is lost under turf and granite blocks. Near the top of the tor a nearly vertical vein consisting essentially of quartz and schorl is traceable downwards to the level of the turf and blocks. As the two veins appeared to lie in the same plane they were traced out beneath the moor-surface, and with the kindly help of Professor A. M. Davies the continuity of the one with the other was proved: the low-level microgranite merged into the high-level quartz-schorl rock through an intermediate facies of pinkish quartzose tourmaline-microgranite. Thus the upper parts of a vein-intrusion which consolidated at depth as a biotitic microgranite (with a little tourmaline) became enriched in those volatile components which promote the formation of tourmaline.

The abundant development of tourmaline in quartzose veins, in granites reddened or otherwise altered by post-solidification pneumatolysis, and in

[1] A. Brammall and H. F. Harwood, 'Tourmalinization in the Dartmoor granite'. Min. Mag., 1925, vol. 20, pp. 319–330.

country-rock affected by emanations from the granite suggests that the most favourable conditions for the genesis of tourmaline are attained at temperatures below that connoted by the Merrivale geodes. Tourmaline arising under these conditions is commonly associated with secondary rutile, brookite, and anatase (singly or in association). In the following sections these titanium-minerals and tourmaline will be examined together.

Rutile, Brookite, and Anatase: Temperatures of Formation.

Rutile, in the form of granules and stout prisms, has been noted as an inclusion in apparently unaltered biotite, but more frequently as an obvious by-product of reactions occurring at magma temperatures and resulting in the production of tourmaline from systems involving biotite.

Plate V, fig. 1 *a*, shows granular rutile in tourmaline, some of the granules being moulded on apatite. Fig. 1 *b* illustrates both the granular and the prismatic habit of such rutile.

Similar rutile has apparently arisen from reactions due to fluxes residual at relatively lower temperatures and now appears in an environment indistinguishable from that shown in Plate IV, figs. 4 and 5.

Secondary rutile (with very rare anatase and no brookite) is unusually abundant in a severely pneumatolysed dike-granite exposed in the disused quarry below the reservoir dam on Holne Moor. In hand-specimens (Plate V, fig. 2 *a*) this rock somewhat resembles the typical Cornish luxulyanite, from which, however, it differs considerably in thin sections (Plate V, fig. 2 *b*). Like the Cornish rock, it is composed of corroded felspars embedded in a groundmass of quartz enclosing tourmaline, but in the Holne Moor type the delicate schorl-needles characteristic of the Cornish rock are quite subordinate to stout euhedral and beautifully zoned prisms. The tourmaline contains 0·56 % TiO_2. Accessory minerals include ilmenite, sphene, fluorite, zircon, and rutile. The habit and relative amount of zircon, the amount of the rutile, and the size of the felspar relics link the original rock with the biotite-rich porphyritic granites. Fluxing precedent to tourmalinization appears to have been more complete and to have occurred at a higher temperature than was the case with typical luxulyanite, from which Mr. J. G. C. Leech informs us he has isolated both brookite and anatase.

Thin delicate needles of rutile have been observed in the groundmass quartz of biotite-granites from several localities; in quartz associated with anatase around tourmalinization-foci in such granites; in reddened

and pneumatolysed types in which rutile is associated with brookite, or anatase, or both; and characteristically in the chloritized biotite of granites showing feeble hydrothermal alteration.'

Brookite has been isolated from many reddened granites. Few of these occurrences lend themselves to the problem in hand, but the two described below are significant.

Foliated, veined, and tourmalinized granite exposed for several yards on the south wall of the entrance to the disused Foggintor quarry shows a series of sharp complex folds traced out by quartz-schorl veins $\frac{1}{2}$ to $1\frac{1}{2}$ inches apart (Plate V, fig. 3). These veins alternate with bands of pinkish felspars lying with their broad surfaces in the foliation planes, which strike roughly east-west.

Plate V, fig. 3 (re-drawn from a field sketch), shows the structure over a portion of the wall. A thrust-plane truncating relatively early folds is clearly traceable, but the regularity of the folds is repeatedly broken by minor shear planes and brecciated patches (Plate V, fig. 4). The folds were certainly produced when the mass was plastic enough to permit the felspars to orientate themselves at right angles to pressure, which was directed roughly north-south and probably from the south. The structure creates the illusion that the folding and the veining are contemporary effects, but this possibility is dispelled by a study of thin sections, which show the veining to be of post-consolidation date. Nevertheless, the foliation-planes were potentially 'open', and favoured penetration by pneumatolytic agents the arteries for which are seen in the immediate vicinity.

The crushed material yields abundant brookite, together with tabular anatase. Biotite is absent, though it is abundant in the normal quarry-rock. The tourmaline (containing 1·05 % TiO_2) occurs mainly as delicate needles massed about the margins of the altered felspars. The etch-test, with hydrofluoric acid, applied to a polished slab of the rock yielded wholly indecisive evidence as to the phase in which the quartz originated, but it revealed the presence of abundant yellow gilbertite developed mainly along the cleavage planes of the felspars. The same test applied to the Holne Moor rock proved the presence of gilbertite in only negligible amount. As this secondary mica is a conspicuous mineral in the Merrivale geodes but dies out beyond the geode-wall in contact with the normal granite, it probably connotes a temperature-range of formation

[1] Such rutile needles in chloritized biotite are also described (with an excellent figure) by E. E. Lowe, 'The igneous rocks of the Mountsorrel district'. Leicester Lit. Phil. Soc., 1926, p. 10, fig. 3.

having its upper limit round about 575°. The features of this tourmalinized granite (yielding brookite and anatase) indicate that in this case tourmalinization was conditioned by a lower degree of fluxing and a lower temperature than in the case of the Holne Moor rock characterized by rutile.

In a feebly reddened and moderately schorlaceous microgranite, containing rutile needles together with scanty brookite and anatase, the quartz shows evidence of having originated as either chalcedony or opal (Plate V, fig. 7). Concerning the stability-range of opal and chalcedony precise data are lacking, but Koenigsberger and Müller (loc. cit.) produced opal in experiments which do not appear to have engaged any temperature higher than 360°. The rock itself records a much lower degree of pneumatolysis than the Holne Moor or Foggintor tourmalinized granites described above, and it is probable that the original rock was modified at temperatures much nearer the lower limit for effective tourmalinization.

Anatase, both tabular and pyramidal, often accompanies brookite, and both varieties of the mineral vary in colour—from deep green, blue, or brown, and almost black through varying shades of green, blue, and brown to pale green, blue, yellow, or almost colourless; particoloured crystals are not uncommon. The relation which doubtless exists between crystal habit and temperature of formation presents a problem still unsolved.

Steel-blue and distinctly pleochroic tabular anatase has replaced apatite in biotite tourmalinized by the reactivity of residual flux at a late stage in the crystallization of the magma (Plate IV, figs. 4 and 5). Such anatase is sometimes accompanied by granular rutile or rutile needles enclosed in quartz. These occurrences suggest for the stability-range of anatase an upper limit which, by analogy with geode-phenomena, is probably round about 575°.

The anatase-brookite association is common in rocks reddened and tourmalinized after consolidation. Examples have already been described.

Significant developments of anatase occur in a facies of the Holne Moor microgranite which is only feebly tourmalinized and contains biotite showing every stage of alteration to chlorite. Flakes of altered biotite are often dense with clusters of rutile needles associated with anatase, the latter forming aggregates of steel-blue pleochroic tablets with the aspect shown in Plate V, fig. 5. In the same rock occasional flakes of apparently fresh biotite contain extremely thin and very minute tablets of pale anatase (Plate V, fig. 6) lying parallel to the biotite cleavages.

These developments of anatase (unaccompanied by brookite) appear to have arisen under simple hydrothermal conditions which involved no fluxing, and little or no tourmalinization. They connote for this mineral the lowest part of the temperature-range of formation so far as this range is determinable from rock in situ.

Summary and Conclusions.

To determine the approximate temperature-range of formation for Dartmoor tourmaline and associated rutile, brookite, and anatase, the authors have applied the work and conclusions of Wright and Larsen, who define two restricted groups of siliceous rocks the quartz in which may be assumed to have originated as the α-phase (i. e. below 575°) and the β-phase (i. e. above 575°) respectively.

Tourmaline-bearing geodes in the Dartmoor granite afford a convenient starting-point. The geode quartz originated as the α-phase; hence tourmaline, demonstrably contemporary in origin with this quartz, originated at a temperature below 575°.

The geode-walls, which also contain tourmaline, merge into tourmaliniferous biotite-granite, in which the normal groundmass quartz originated as the β-phase, i.e. above 575°. Tourmaline which arose in the geode-walls therefore connotes a growth-temperature having 575° as a mean. This range is extended upwards to $575° + x°$ on the evidence of tourmaline-growth (1) demonstrably contemporary in origin with quartz in the normal groundmass, or with biotite, (2) euhedrally developed and appearing as inclusions in biotite, or in porphyritic felspar, (3) developed in certain types of quartz-tourmaline nodes, (4) in quasi-graphic intergrowth with quartz in graphic granites, and (5) in 'reaction relation' to felspar and biotite as a product of reactions for which temperatures of residual magma are indicated. This upper limit, $575° + x°$, may conceivably approach 800°, the point above which the crystallization of quartz direct from the magma would not occur.

The temperature-interval between 575° and the low temperature connoted by simple hydrothermal action accompanied by little or no tourmalinization is bridged by tourmaline-growth (1) in granites reddened and often profoundly altered by post-solidification pneumatolysis, (2) in quartz-tourmaline veins, (3) in granite tourmalinized under conditions favourable to the genesis of opal or chalcedony, which subsequently inverts to quartz, and (4) in country-rock affected by emanations from the granite.

How far this temperature-range of tourmaline-growth may be extended downwards to include possible authigenic tourmaline is uncertain.[1]

Parallel observations on the genesis of rutile, brookite, and anatase lead to conclusions applicable solely to occurrences of these minerals in this granite. The fact that the biotite in the granite is titaniferous and is associated with ilmenite and, to a less extent, with sphene, is a factor favourable to the genesis of rutile, &c., as secondary minerals.

Hautefeuille [2] synthesized anatase by decomposing titanic fluoride with aqueous vapour at about the boiling-point of cadmium (770°), and brookite by the action of hydrofluoric acid on titanic chloride at a temperature not higher than the boiling-point of zinc (920°). Hence anatase has been produced at a temperature only 30 degrees below that at which quartz becomes unstable,[3] and brookite, at a temperature approaching that at which quartz would invert to either tridymite or cristobalite. Both syntheses were therefore effected at temperatures consistent with crystallization direct from magma, but neither brookite nor anatase occurs as a direct separation from the magma. Hautefeuille's syntheses engaged only simple systems offering for the liberated titanic oxide no claimants in the form of other oxides such as lime, ferrous oxide, magnesia, silica, &c. In the complex magma-system such oxides were available, and their combinations with titanic oxide achieved titaniferous biotite, titaniferous tourmaline, ilmenite, and sphene.

Rutile originated (1) as a primary or as a secondary mineral at temperatures above that at which crystallization from the magma attained completion, (2) as a secondary mineral in high-temperature borosilicate fluxes involving biotite, felspar, and ilmenite, (3) as delicate needles over a temperature-range approximately co-extensive with the stability-range of tourmaline, and especially at the relatively low temperatures consistent with the simple hydrothermal alteration of biotite.

The upper limit of the stability-range for anatase is lower than that for rutile, but higher than that for brookite, and is located within the

[1] Such tourmaline, in the form of extremely minute pale greenish hemimorphic prisms, has been observed in the Skiddaw Slate and in certain Bolivian phyllites. A. Brammall, 'Reconstitution processes in shales, slates, and phyllites'. Min. Mag., 1921, vol. 19, pp. 211–224.

[2] P. Hautefeuille (1865), cited by Clarke, loc. cit., pp. 354–355.

[3] Quartz is unstable at all temperatures above 800° (Day and Shepherd, loc. cit.), is metastable above 870° (White, loc. cit., p. 30), is transformed to tridymite at 870° ± 10° (C. N. Fenner, Amer. Journ. Sci., 1913, ser. 4, vol. 36, p. 331), tridymite passing over to cristobalite at 1470° ± 10° (Fenner).

temperature-range for crystallization from residual magma yielding quartz and tourmaline to the groundmass. The lower limit of the stability range for brookite is higher than that for anatase and rutile. The range for brookite seems to lie within that for anatase.

The temperature-range of formation thus approximately defined for each of these titanium minerals is that determinable from observations of modes of genesis in a particular granite affected by pneumatolytic agents at a late stage in its cooling history.

Taking into consideration occurrences of the three species developed authigenically in sedimentary rocks, as distinct from metamorphic rocks, the temperature-range of formation for all three species must be extended downwards to points as yet undetermined.

The authors express their thanks to Professor W. W. Watts (Geology Department) and Professor H. B. Baker (Chemistry Department) for laboratory facilities kindly placed at their disposal, and to Dr. H. H. Thomas (H.M. Geological Survey) for examining several of the rock-sections described in this paper and confirming certain identifications of anatase.

Description of Plates IV and V.

Letters on the figures: F (Felspar), Q (Quartz), T (Tourmaline), B (Biotite), Ru (Rutile), An (Anatase), Ap (Apatite), I (Ilmenite), Z (Zircon).

Plate IV.

Fig. 1. Tourmaline almost contemporaneous with quartz in a medium-grained granite composed of microperthite, microcline, albite, biotite, pinite, and the common accessories. Hollow Tor. (×9.)

Fig. 2. Quasi-eutectic intergrowth of quartz and tourmaline in pegmatite. Merrivale quarry. (About one-half actual size.)

Fig. 3. A similar intergrowth around and penetrating orthoclase in a garnetiferous graphic granite. The graphic quartz carries tourmaline. Widdecombe. (About actual size.)

Figs. 4 and 5. Secondary brown tourmaline in reaction relation to biotite and felspar, and accompanied by much quartz. Tourmaline has invaded the biotite at right angles and parallel to cleavage. The forked body in the tourmaline of fig. 4, and the two cigar-shaped bodies in the tourmaline of fig. 5 are replacements of apatite by steel-blue anatase. Biotite-cordierite-garnet-granite. Sweltor quarry. (×16.)

Fig. 6. The larger of the two cigar-shaped bodies in the tourmaline of fig. 5. Anatase and fluorite replacing apatite.

Fig. 7. (*a*) Fringe-like outgrowth from biotite; sometimes tourmalinized at contact with quartz.

(*b*) Irregular tourmaline-growth in a quartz 'pool' flanked by biotite. The growth-periods for biotite and tourmaline overlap.

(*c*) A minute euhedron of brown tourmaline occurring, like zircon, apatite, and monazite, as an inclusion in biotite.

(*d*) Showing overlap of the growth-periods of biotite, ilmenite, and tourmaline.

Highly biotitic vein-granite, Widdecombe. (×30.)

Plate V.

Fig. 1. Secondary particoloured tourmaline produced mainly at the expense of biotite, with the development of yellow-brown rutile as granules (fig. 1 *a*), as granules and prisms (fig. 1 *b*). Granite, Wittabarrow. (×15.)

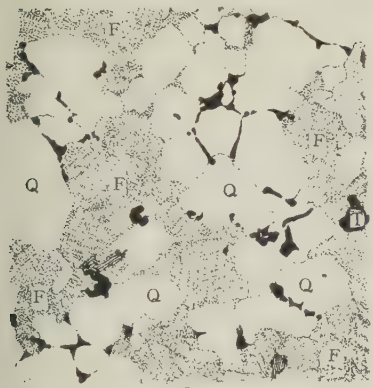
Fig. 2. Tourmalinized dike-granite. Hand-specimens (fig. 2 *a*) recall luxulyanite, but thin sections (fig. 2 *b*) show euhedral zoned prisms dominant over the acicular schorl characteristic of luxulyanite. The rock figured contains abundant rutile, with very rare anatase and no brookite. Holne Moor reservoir quarry. (Fig. 2 *b*, ×18.)

Fig. 3. Quartz-schorl veins tracing out pressure-folds and thrust-planes in tourmalinized granite yielding brookite, anatase, and rutile needles. Foggintor quarry.

Fig. 4. A polished block of the granite described above. Thrust-planes break the continuity of the folds.

Figs. 5 and 6. Aggregates of steel-blue anatase, and pale-yellow tablets of anatase associated with rutile needles in chloritized biotite (diameters, 0·3–0·9 mm.). Microgranite, Holne Moor.

Fig. 7. Schorl needles associated with anatase, brookite, and rutile needles in secondary quartz which originated as either opal or chalcedony. Reddened granite, Top Tor. (×28.)



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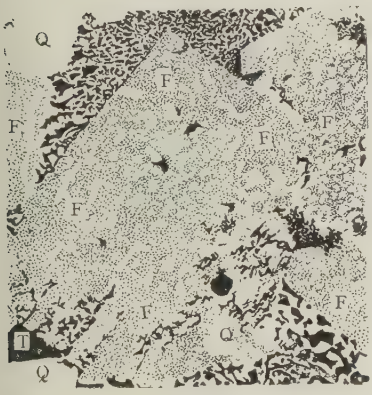

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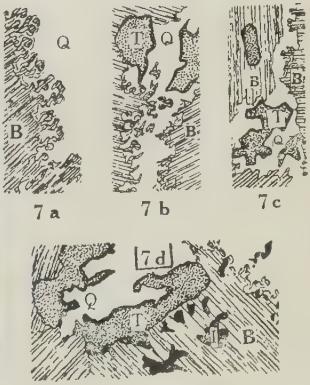
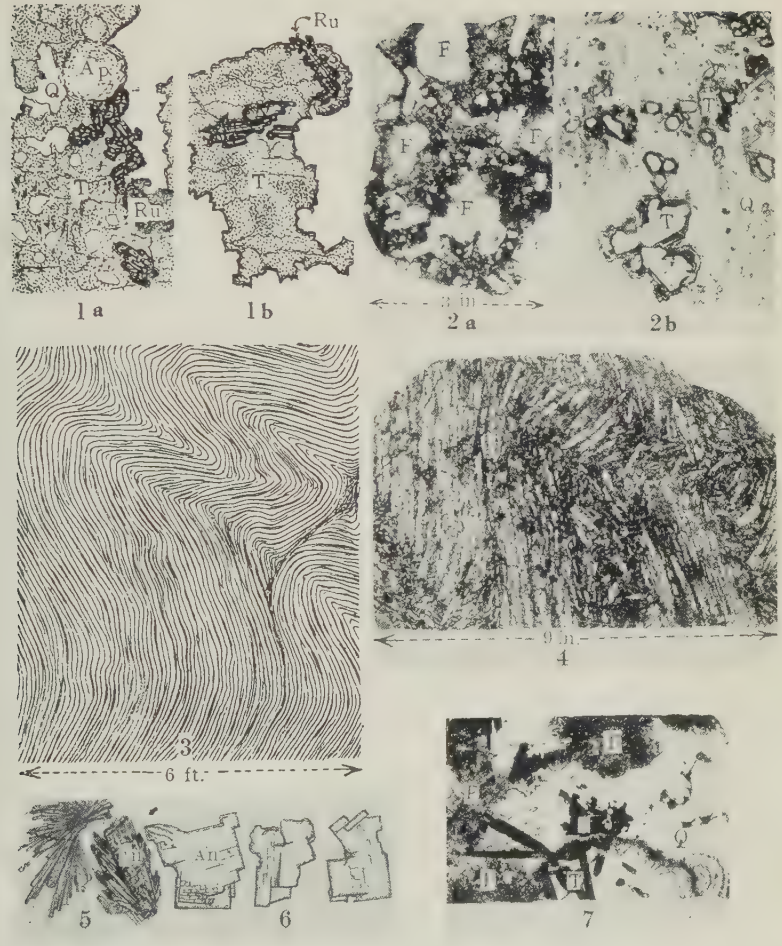


A. BRAMMALL AND H. F. HARWOOD: TOURMALINE, RUTILE, BROOKITE, AND ANATASE IN DARTMOOR GRANITE.



A. BRAMMALL AND H. F. HARWOOD: TOURMALINE, RUTILE, BROOKITE, AND ANATASE IN DARTMOOR GRANITE.

On laurionite and associated minerals from Cornwall.

By Arthur Russell.
With a note on paralaurionite.
By Prof. A. Hutchinson, M.A., Ph.D., F.R.S.

[Read January 10, 1922.]

THE two exceedingly interesting specimens which form the subject of the present notes came under my observation in the following manner. In 1905 there was sold by public auction in London an old and very fine collection of minerals, mostly Cornish, which had been formed by John Hawkins, F.R.S. (b. 1758, d. 1841), of Trewithen, Probus, Cornwall; a gentleman well known in his day both as a scientist and traveller. The major part of the collection unfortunately left this country, having been purchased by the dealer F. Krantz of Bonn. A few lots were, however, bought by myself, and one of these contained the first specimen to be here described.

This specimen consists of one-half of a small geode 7×5 cm. formed of brown and velvety black limonite, some partially altered chalybite, ferruginous crystalline quartz, and a little galena. In this geode and upon the limonite are emplanted several very brilliant crystals of phosgenite, one large tabular crystal of anglesite, and numerous smaller crystals of laurionite. The specimen had no label, but besides being certainly Cornish, it came, almost without doubt, from the silver-lead mine of Wheal Rose in the parish of Sithney. With this specimen there were others of cerussite labelled Wheal Pool (a neighbouring mine). Further, the geode exactly resembles similar geodes containing cerussite and anglesite which have been found by myself on one of the old dumps at Wheal Rose. The limonite on all of the specimens is exceedingly characteristic of the locality, showing evidence of being pseudomorphous after chalybite.

The other specimen, which is in the Brooke collection at Cambridge, (no. 2302) is especially referred to by Greg and Lettsom under cromfordite (phosgenite) as being the only specimen of that mineral known

to be from Cornwall. An idealized figure of one of the crystals is given and it is stated that the locality is believed to have been Huel Confidence, New Quay, St. Columb Minor,[1] this locality, as also measurements of one of the phosgenite crystals, being recorded in H. J. Brooke's notebook which is preserved along with the collection. Through the kindness of Professor A. Hutchinson I was able to examine the specimen, when it was at once seen that it very closely resembles the one previously described. It likewise consists of a portion of a small geode of velvety black limonite, in which are several very well-defined crystals of phosgenite exactly similar in habit and presenting the same forms as those on the specimen from the Hawkins collection. In addition, however, to the phosgenite there are platy crystals of a mineral which Professor Hutchinson readily undertook to examine and which he has proved to be the rare species paralaurionite, described by Dr. Herbert Smith as a new mineral in 1898. There is no laurionite upon this specimen, the only other mineral present being a little pyromorphite on the outside of the geode. The particulars as to the paralaurionite which follow have been contributed by Professor Hutchinson.

Laurionite.

[$PbCl_2 . Pb(OH)_2$. Orthorhombic, $a : b : c = 0{\cdot}7385 : 1 : 0{\cdot}8346$.[2]]

The crystals of laurionite are colourless and translucent and bladed in form, attaining a length of 4 mm. Fig. 1 represents the general habit which closely resembles one of the figures (fig. 3) given by Köchlin of Laurion crystals.[3] Two crystals were measured, one a detached one, the other on the specimen. The following forms are present: b (010), m(110), n(120), d(012), and the prominent but somewhat doubtful form p(141). The principal angles observed compared with those on Laurion crystals described by Dr. Herbert Smith are given in the following table:

Angle.	Calculated.	Observed mean Laurion.	Observed Cornwall.
(010) : (120) ...	34° 0′	34° 6′	34° 10′
(010) : (110) ...	53 33	53 45	53 46½
(010) : (012) ...	67 20	67 21	66 28½
(010) : (141) ...	24 19½	19 0–27° 12′	22 27–22° 46½′

[1] R. P. Greg and W. G. Lettsom, 'Manual of the Mineralogy of Great Britain and Ireland', 1858, pp. 421–423.

[2] The axial ratios given are those deduced by Dr. G. F. Herbert Smith from measurements on crystals from Laurion, Min. Mag., 1899, vol. 12, p. 102.

[3] R. Köchlin, 'Ueber Phosgenit und ein muthmasslich neues Mineral von Laurion'. Ann. naturhist. Mus. Wien, 1887, vol. 2, pp. 188–190.

The faces as a whole appeared to be etched and afford multiple images, with the exception of m (110) which gives good reflections. As in the case of the Laurion crystals the faces of b (010) are striated parallel to their intersection with the pyramid p (141), the latter being possibly a vicinal form as suggested by Dr. Herbert Smith. The edges formed by the intersection of the faces p (141) are always more or less curved, thus giving rise to the bladed form.

No interference-figure can be seen looking through (010). The

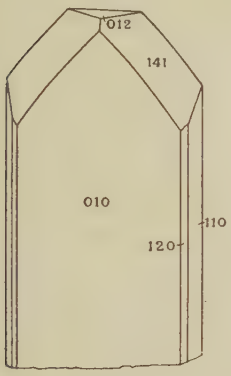


Fig. 1. Crystal of Laurionite, from Wheal Rose, Sithney, Cornwall.

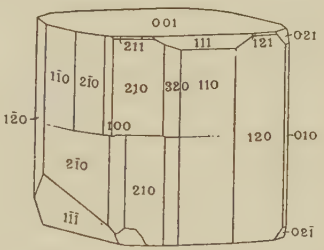


Fig. 2. Crystal of Phosgenite, from Wheal Rose, Sithney, Cornwall.

crystals when powdered are partially soluble in boiling water. The presence of lead and chlorine was determined.

Of the three associated minerals, laurionite, phosgenite, and anglesite, the laurionite appears to have been the last formed, and partially invests the other two.

Paralaurionite (by Prof. A. Hutchinson).

[$PbCl_2 . Pb(OH)_2$. Monoclinic, $a : b : c = 2{\cdot}7036 : 1 : 1{\cdot}8019$, $\beta = 62° 47'$.[1]]

The identification as paralaurionite of the platy crystals on the Brooke collection specimen no. 2302, referred to above, rests on the following observation:

The crystals are long narrow thin plates without for the most part any terminal faces and when measured gave angles consistent with the supposition that they are crystals of paralaurionite elongated along the symmetry-axis and twinned about a(100) with the faces of a large and

[1] G. F. H. Smith, Min. Mag., 1899, vol. 12, pp. 108, 183.

those of $c(001)$ small. Thus on one crystal the following angles were observed: $a\,c = 62° 50'$, $c\,\underline{c} = 53° 54'$, $\underline{c}\,\underline{a} = 63° 21'$, $\underline{a}\,c' = 62° 45'$, $c'\underline{c}' = 54° 15'$, $\underline{c}'a = 62° 55'$, which agree well with the angle $a\,c = 62° 47'$ and the consequent angle $c\,\underline{c} = 54° 26'$ given by Herbert Smith. There is an excellent cleavage parallel to $c(001)$. Indications of other faces in the zone $a\,c$ were observed, and it is probable that $h(\bar{2}01)$ is present on some crystals as a very narrow face.

The important face $m(110)$ mentioned by Herbert Smith was not observed, but a face making an angle of 24° 24′ with a was found instead. Simple indices cannot be assigned to this face ((510) would correspond to an angle from a of 25° 38′) and it is probable that it is an accidental face produced where one crystal has come in contact with another. It was, however, sufficiently plane to enable a rough determination of the refractive index for light vibrating parallel to the symmetry-axis to be made, by using as a prism this face and $a'(\bar{1}00)$. The result for sodium-light is 2·118, which is somewhat smaller than the value 2·146 given by Herbert Smith.

On examining one of the thin plates in convergent monochromatic (sodium) light an interference-figure was seen transverse to the length of the plate and similar to that given by a twinned diopside. The same phenomenon was noted by Herbert Smith in the case of paralaurionite and was mentioned by him as specially characteristic of this substance and as affording the best means of distinguishing it from laurionite and fiedlerite. The fact that this character is exhibited so clearly by the Cornish material provides strong confirmative evidence that the identification with paralaurionite is correct.

Phosgenite.

[$PbCO_3 . PbCl_2$. Tetragonal, $c = 1·0889$.[1]]

The crystals of phosgenite on the specimen from the Hawkins collection are exceptionally beautiful, being almost transparent, possessing a high lustre, and lying on a black background of limonite. The largest measures 6 mm. along the vertical axis. Fig. 2 represents one of the crystals which was measured on the specimen, and is an accurate representation, with the exception of the back where it is attached to another crystal. The forms present are $c(001)$, $a(100)$, $m(110)$, $l(320)$, $u(210)$, $o(201)$, $x(111)$, $s(211)$. It will be seen from the drawing that the

[1] Axes and letters of forms as in V. Goldschmidt, 'Atlas der Krystallformen', 1920, vol. 6, p. 150.

crystal is in part an intergrowth of two individuals one overlapping the other, the faces of the two individuals, though unequally developed, being in parallel position. The prism-faces, though brilliant, are all vertically striated and afford banded images. The following were the principal angles observed:

Angle.	Calculated.	Observed.
(100) : (210)	26° 34′	26° 32½′
(100) : (320)	33 41	34 8
(100) : (201)	24 40	24 16½
(110) : (111)	33 0	33 0
(210) : (211)	22 20	22 17

In the William Phillips collection at Liverpool are several small loose aggregates of crystals of phosgenite which are described in the Sale Catalogue dated 1829 as 'No. 1232, Murio-carbonate of lead in detached transparent crystals. Huel Confidence, near New Quay, Cornwall.' Accompanying these are Phillips's freehand drawings and rough measurements of three of the crystals. The habit is nearly the same as that of the two specimens already described, the forms present being also the same. One of the aggregates shows a little attached limonite and chalcopyrite. It was probably from this source that the Brooke specimen had ascribed to it the locality Huel Confidence.

Anglesite.

[$PbSO_4$. Orthorhombic, $a : b : c = 0{\cdot}7852 : 1 : 1{\cdot}2894$.[1]]

One large colourless and transparent crystal of anglesite 1 cm. in length has grown across the bottom of the geode on the Hawkins specimen. It is tabular parallel to $a(100)$, and is bounded by narrow faces of $m(110)$ and $d(102)$, fig. 3. A small crystal growing from the large one was detached for measurement and identification. A specimen collected from the mine dump by myself in 1921 shows a rough etched prismatic crystal of anglesite 1½ cm. in length, occupying a small cavity, lined with deep-brown crystals of quartz, in limonite with some galena.

Thanks to Mr. George Penrose, Curator of the Royal Institution of Cornwall Museum, Truro, I have been able to examine two specimens of anglesite from Wheal Rose, belonging to the Philip Rashleigh collection. The first of these, no. 405 in the MS. catalogue of the Rashleigh collection, is described as 'White four-sided tabular crystals of lead with parallelogram form, with edges replaced, on iron ore. Huel Rose.' It shows

[1] Axes and letters of forms as in Dana's 'System', 6th edition, 1892.

numerous white translucent crystals up to 5 mm. in length scattered over the interior of a limonite geode, with spots of chalcopyrite. A typical crystal was measured. It is tabular parallel to $a(100)$ and shows the forms $a(100)$, $m(110)$, $n(120)$, $d(102)$, fig. 4. The second specimen no. 352 is described as 'Transparent crystals of lead ore with six-sided

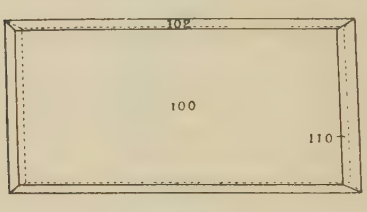


Fig. 3.

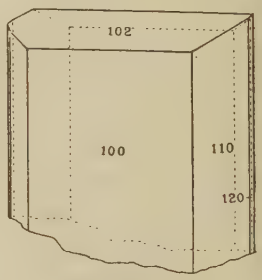


Fig. 4.

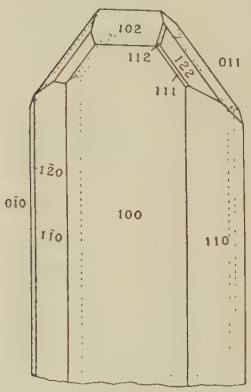


Fig. 5.

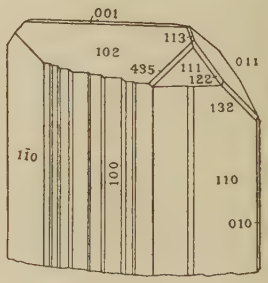


Fig. 6.

Figs. 3–6. Crystals of Anglesite, from Wheal Rose, Sithney, Cornwall.

prisms near flat beviled pyramids. Huel Rose, G.C.F.'[1] It shows slightly brownish flat bladed crystals of anglesite up to 5 mm. in length occupying a cavity in brown limonite with a little quartz and chalcopyrite on the back of the specimen. Two crystals were selected for measurement. Fig. 5 shows the forms $a(100)$, $b(010)$ one face only, $m(110)$, $n(120)$, $d(102)$, $o(011)$, $r(112)$, $z(111)$, $y(122)$; Fig. 6 the forms $a(100)$, $b(010)$, $c(001)$, $m(110)$, $d(102)$, $o(011)$, $g(113)$, $z(111)$, t(435), $y(122)$, $s(132)$. The prism-faces on this crystal are deeply furrowed owing to repeated alternations of (100) and $(1\bar{1}0)$. A narrow face was

[1] George Croker Fox, Senior.

also observed lying between (435) and (111), the angle to (111) being 4° 13′; to this, however, no definite indices can be assigned. A specimen labelled anglesite from Wheal Rose in the Penzance Museum proved on examination to be cerussite.

Cerussite.[1]

Beautiful specimens may still occasionally be found by breaking open geodes of limonite which lie on the small and now nearly overgrown dump at the northernmost shaft. The interior of these geodes consists of mamillary velvet black limonite upon which are implanted thin flat translucent twinned crystals of cerussite up to 8 mm. in length. These crystals are tabular parallel to $b(010)$, twinned on $m(110)$, and show the forms $b(010)$, $m(110)$, $i(021)$, $p(111)$, fig. 7. Small acicular crystals also occur and more rarely bipyramidal crystals, combinations of $p(111)$ with $i(021)$ and $m(110)$, showing polysynthetic growths and measuring up to $1\frac{1}{2}$ cm. along the vertical axis.

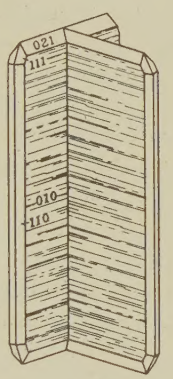


Fig. 7. Twin-crystal of Cerussite, from Wheal Rose, Sithney, Cornwall.

Pyromorphite.

This mineral occurred at Wheal Rose in some abundance. It forms small (up to 6 mm. in length) bright grass-green to greenish-yellow hexagonal prisms often partly hollow or slightly barrel-shaped, $m(10\bar{1}0)$, with occasionally narrow faces of $a(11\bar{2}0)$. It incrusts sugary quartz, and invests pyramidal crystals of quartz or more rarely pseudomorphous lenticular crystals of limonite after chalybite.

Wheal Rose[2] and the adjoining mines Wheal Penrose and Wheal Pool are probably the oldest lead mines in Cornwall, records of their working

[1] Axes and letters of forms as in Dana's 'System', 6th edition, 1892.

[2] J. Carne, Trans. Roy. Geol. Soc. Cornwall, 1822, vol. 2, p. 344.

'Notes on the Excursions of the Helston Branch of the Miners' Assoc. Cornwall and Devon', 1864, p. 11.

H. Stephens, 'Mineral phenomena of Huel Rose'. Ann. Rep. Roy. Cornwall Polytechnic Soc., 1871, no. 39, pp. 77–80.

In 'The Geology of the Lizard and Meneage', Mem. Geol. Survey, 1912, pp. 257–258, a misquotation respecting this mine appears—it is stated that 'small vugs containing phosphate and arseniate of iron were found', whereas it should read 'phosphate and arseniate of lead'. This error is repeated in 'The Special Reports on the Mineral Resources of Great Britain', 1921, vol. 21, p. 10.

dating back to 1625. The main lode at Wheal Rose has a direction nearly due north and south magnetic, and outcrops on the low cliff three-quarters of a mile south-east of Porthleven (6-inch ordnance map, 76 SW.). The mine was worked to a depth of 54 fathoms, the southern levels extending under the sea and the mine water being extremely salt. The upper portion of the lode consists of limonite and comby crystallized quartz with galena, and a little chalcopyrite and blende. In depth the limonite changed to chalybite and this during the last working, about 1864, was mined as an iron ore. The galena contained 60 ounces of silver to the ton.

Several small lead mines were formerly worked on lodes outcropping in the cliffs near New Quay and one of these may once have been known as Wheal Confidence. A search of old mining records has only established the fact that there was a Wheal Confidence at work in Cornwall during the years 1830–1, but whether a lead mine and where situated is not stated.

There can be little doubt that both the Hawkins and Brooke specimens here described came from the same locality. In connexion with the origin of the two oxychlorides it is significant that at Wheal Rose salt water had access to the lead lode. At Laurion, Greece, the minerals laurionite, paralaurionite, phosgenite, and anglesite have all been formed in ancient lead slags which for some 2,000 years have been exposed to the action of sea-water.

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Oxford: Printed by John Johnson, at the University Press

RE-PRINT LITHO by Colonna Press Limited, Queensway Hemel Hempstead. Herts.